Applied Energy 156 (2015) 618–627

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Syngas-based annex concepts for chemical energy storage and improving flexibility of pulverized coal combustion power plants

Christian Wolfersdorf *, Kristin Boblenz, Robert Pardemann, Bernd Meyer

TU Bergakademie Freiberg, Institute of Energy Process Engineering and Chemical Engineering, Fuchsmuehlenweg 9, 09599 Freiberg, Germany

HIGHLIGHTS

- Annex concepts with coal gasification and synthesis unit linked to PCPP.
- Capital costs reduced by 21% because of shared infrastructure with PCPP.
- Annex improves flexibility of existing power plants.
- Integration of green power with annex concepts by optional electrolysis.

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 7 July 2015
Accepted 14 July 2015

Keywords:
Coal gasification
Chemical energy storage
Process simulation
Methanol
SNG
Polygeneration

ABSTRACT

The increasing supply of fluctuating power from renewable sources not only in Germany requires improved capability for part load operation of conventional power plants in combination with electricity storage solutions to ensure the security of electricity supply.

Different operational concepts are introduced to link a base load lignite-fired power plant with a small sized coal gasification and synthesis unit (annex unit). The annex unit comprises coal gasification, water electrolysis (optional), gas treatment and subsequent synthesis of storable fuels or chemicals (SNG, methanol). This unit is a power sink and chemical energy storage in times of renewable excess electricity, which reduces the overall net power output to the grid and lifetime-consuming start-ups and shutdowns of the power plant. In addition, the annex unit can also provide peak load in line with the actual demand. The concepts are modeled and evaluated regarding efficiency, CO_2 emissions and the ability to reduce the minimal load of the total plant.

The study was performed for an annex unit with 500 MW(th) gasifier linked to a 2264 MW(th) power plant. As a result, the annex concept with an additional 150 MW(el) electrolysis unit can reduce the power output to the grid from 50% minimal load to 33–34% during "electricity storage" and can increase the power output to the grid from 100% nominal load to 152–154% during "peak load generation". The improved flexibility of the annex concepts is accompanied by a reduction of the total efficiency (power plant and annex with re-combustion of the produced fuel) and a subsequent rise of the specific CO_2 emissions. Thermal efficiencies of annex concepts without electrolysis result in 63.1% for SNG and 55.5% for methanol.

The capital expenditure of an annex unit (without electrolysis) is 21% lower than for an equally sized stand-alone unit because of taking advantage of the shared infrastructure of the coupled power plant.

Despite the growing share of green power there will be a significant demand for base load. The introduced annex concepts can contribute to flexibility and economics of existing conventional coal-fired power plants.

1. Introduction

The worldwide electricity demand is reported to rise by 1.6–2.4% per year (2012–2040). Renewables-based electricity generation nearly triples in that time [1]. As a specific example, in Germany their share of gross electricity generation has increased from 6% in 2000 to about 20% in 2011 and shall reach 35% in 2020 and even 85% in 2050 [2–4]. Intermittent power sources like wind and solar power require both electricity storage solutions [5] to handle the increasing amounts of excess electricity [6] and improved flexibility of conventional power plants as back-up to ensure the security of

* Corresponding author. Tel.: +49 3731394512.
E-mail address: christian.wolfersdorf@iec.tu-freiberg.de (C. Wolfersdorf).

http://dx.doi.org/10.1016/j.apenergy.2015.07.039

Abbreviation and Nomenclature

AGR	acid gas removal
ASU	air separation unit
Aux	auxiliary
BEC	Bare Erected Costs
CR	carbon retention
DC	dried coal
Emis	emissions
EOR	enhanced oil recovery
EPCM	Engineering, Procurement and Construction Management
Equiv	equivalent
EST	electricity storage
GT	gas turbine
IGCC	Integrated gasification combined cycle
MeOH	methanol
PCPP	pulverized coal combustion power plant
PLG	peak load generation
RC	raw coal
SF	storable fuel
STP	standard Temperature, Pressure
SNG	synthetic natural gas
TOC	Total Overnight Capital
TPC	Total Plant Costs
$\Delta H_{R,0}$	standard enthalpy of reaction (kJ/kmol)
HHV	higher heating value (MJ/kg)
LHV	lower heating value (MJ/kg)
$\dot{n}_C$	carbon mole flow rate (kmol/s)
P	power (MW)
$\overline{P}$	averaged power (period of time) (MW)
P_{el}	electric power (MW(el))
P_{th}	thermal power (LHV-based) (MW(th))
SN	stoichiometric number (kmol/kmol)
η	efficiency (%)
ξ	efficiency (period of time) (%)

energy supply [7]. However, flexibility and part load capabilities of large scale coal-fired power plants are limited and linked to a reduction of lifetime [8,9].

Coal gasification with subsequent synthesis of storable fuels is a well investigated technology [10,11]. Kopyscinski et al. [10] present a comprehensive review about SNG production from coal and dry biomass. The predicted future deployment is highlighted by a number of announced international projects. The key challenges for future developments in coal gasification are the reduction of costs and the increase of flexibility [12,13]. The investment and operational costs of stand-alone coal gasification concepts are high compared to oil-based chemicals because of solids handling, gas purification and treatment of effluent streams [14]. The increasing interest in coal-based polygeneration power plants is aiming at product flexibility and resource utilization for higher total efficiencies and improved economics of the overall plant [15–18]. The paper of Li et al. [15] addresses coal-based co-generation of SNG and electricity. Their results show a higher overall efficiency if a part of the chemical unconverted gas is recovered for the combined cycle instead of being recycled for methanation. Process chains with coal gasification and synthesis are suitable for the integration of excess electricity, e.g. by an additional water electrolysis as reported by Pardemann et al. [13]. A similar approach is investigated by Buttler et al. [19] for decentralized stand-alone plants with combined cycle. Related concepts are discussed by Clausen et al. [20], which combine biomass gasification, water electrolysis and autothermal reforming of natural gas or biogas for the production of methanol. The study of Herdem et al. [21] proposes a combined system of coal gasification and alkaline water electrolysis for hydrogen production at low CO_2 emissions. Another approach to increase the flexibility of coal-based electricity generation is syngas storage in Integrated gasification combined cycle (IGCC) power plants [22,23].

However, the discussed studies have in common, that an increase of flexibility is accompanied by increased capital costs. A novel concept aiming for both, cost reduction and flexibility increase, links a pulverized coal combustion power plant (PCPP) with a coal gasification and synthesis unit of lower thermal capacity (annex unit), dividing the overall coal mass flow into one part for the PCPP and a smaller part for syngas production.

As indicated in Fig. 1, the annex unit comprises coal gasification, water electrolysis, gas treatment, auxiliary plants (e.g. air separation unit ASU, coal preparation and optional water electrolysis) and synthesis of fuels or chemicals (SNG, methanol), that can be used externally or for peak load generation. Cost reductions can be realized by using the infrastructure of the PCPP. The flexibility improvement is achieved by:

- the auxiliary power consumption of the annex unit forming a power sink for the linked PCPP to avoid lifetime-consuming start-ups and shutdowns during high renewable power supply,
- the possibility of peak load generation by re-combustion of the stored fuel,
- additional integration of excess electricity by electrolysis technology.

In this paper a steady-state process model is described to analyze the techno-economic synergies for the proposed system. Several operational concepts are derived and investigated in different cases of power supply. The main scope of this work is the assessment of the capital expenditure reduction and the potential evaluation for contribution to flexibility improvements regarding part load and peak load capabilities of the system.

2. Process model

The annex unit, including auxiliary plants and gas turbines are modeled using Aspen Plus® based on minimization of Gibbs energy. All submodels are steady-state, without considering load changes by dynamic modeling. The PCPP and alkaline electrolysis are characterized by literature values for efficiency, power output and auxiliary power consumption.

2.1. Gasification island

The coal preparation consists of fluidized bed steam drying and pulverization for entrained flow gasification. The coal analysis of the dried coal (DC) is given in Table 1. Oxygen with a purity of 98 vol.% is produced by a cryogenic air separation unit (ASU). The ASU is modeled as low pressure configuration based on a pressure of the high pressure column of 5.6 bar. Air integration is not provided because of the temporal decoupling of annex unit and gas turbines. The flow sheets of coal preparation and ASU are given